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Sustainable Design and Building Information Modelling: Case Study of Energy Plus House, Hieron's Wood, Derbyshire UK

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Abstract

In this paper the method for sustainable design analysis (SDA) integration with building information modelling (BIM) is explored, through the prism of a complex case study based research. BIM model federation and integration challenges are reported, including issues with combining geometry and managing attribute data. The research defines SDA as rapid and quantifiable analysis of multitude of sustainable alternatives and 'what if' questions posed by a design team during the early stages of the project, when the benefits of correct decisions can significantly exceed the actual investment required. The SDA concept and BIM integration findings are explained from conceptualisation to calculation stage, emphasising the importance of an iterative over a linear approach.
The research approach adopted has led to more informed sustainable solutions at earlier stages of project development, with a generally lower level of development (LOD) and computational/modelling effort required.

Keywords: Sustainable Design Analysis, BIM, Case Study

Nomenclature

BIM	Building Information Modelling
SDA	Sustainable Design Analysis
SBE	Smart Built Environment

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1. Introduction

This case study based research presents the method and technology for integration of sustainable design analysis (SDA) with building information modelling (BIM). The uptake of building information modelling (BIM) has been rapid in recent years, and the research published into its interoperability and project collaboration aspects since its inception is considerable [1]. However, whilst a significant amount of work has been undertaken on the technical interoperability aspects of BIM and sustainable design analysis (SDA) [2], the practice is still fairly new and general practitioners are perplexed by both the amount and complexity of software solutions on the market. Therefore, given that the BIM interoperability is technically possible, what benefits can it bring, how well can it be adopted and in time can it prove itself over the conventional stand-alone approach?

2. SDA and BIM Integration

As defined in [3], “sustainable design analysis could be referred to as rapid and quantifiable feedback on diverse sustainable alternatives and ‘what if’ questions posed by a design team and client during the early stages of the project”. Its main purpose is to maximise environmental versus cost benefits of the project through informed choices based on timely feedback, such as building materials and construction specifications, energy consumption and generation, CO_2 emissions, water use and harvesting, waste and pollution management. Indeed, there are other aspects which are inherently linked and therefore considered, such as: functional (constructional, operational), human (safety and security, comfort health and wellbeing), socio-cultural (context, sense of place, aesthetics) and economical (profits, environmental impact versus cost analysis, life cycle costing etc.) [3].
Krygeil and Nies [5] propose a holistic approach, a form of sustainable design chronology that considers the following facets:

- Understanding climate, culture and place
- Understanding the building typology
- Reducing the resource consumption need
- Using free local resources and natural systems
- Using efficient man made systems
- Applying renewable energy generation systems
- Offsetting negative impacts

Sustainable design analysis broadly follows two stages; conceptualisation and calculation [3]. Each necessitate different design methods and serve different purpose for a distinct outcome. Conceptualisation is about challenging, interrogating and problem solving, understanding broader creative and rational constructs, the macro scale and the directional decisions. The calculation stage is less directional and more analytical in its nature, aiming to quantify qualitative directional decisions and compare different design alternatives
The site and building(s) are assessed considering microclimate, wind parameters, surrounding surfaces, landscape and topology, massing and orientation, the form and nature of the building envelope, location and percentage of fenestration, zoning, day-lighting, heating and cooling loads, air change rate, occupant behavior, services and the range of acceptable indoor climate variation [4]. This indeed is not an extensive list, nor should it be considered isolated from the design process itself. Each and every design must be a unique and contextually sensitive place making response to the site location and client brief, one that fully takes into the account environmental, social and economic aspects, including whole life cycle costing analysis [6].
There is a growing number of environmental performance building analysis programmes on the market, such as Integrated Environmental Solutions © IES <VE>, Autodesk © Revit, Ecotect, Vasari and Green Building Studio, Graphisoft © EcoDesigner STAR, EDSL © TAS Building Designer, EDR California © eQuest, U.S. Department of Energy © Energy Plus etc. Without favouring one over another, they do vary in terms of their results accuracy and data representation, the knowledge required to operate and the way in which they interpret the results, visual display and input/output type, building regulations compliance etc. Programmes range from simple, user friendly and often free tools to extensive, sophisticated software that require expert knowledge use by specialist

sustainable design building consultants. The range of applications include site analysis of PV potential, right to light, sun path and solar stress diagrams, solar exposure, heating and cooling load calculations, thermal, solar gain and shading design, lighting, acoustics, ventilation, computational air flow fluid dynamics (CFD) analysis, and number of other functions. Decision on choice of software and its interoperability and integration with office practice is perplexing to most companies and remains a big challenge [7].
If fully integrated within the design process, most SDA and BIM data needed to support design decisions and subsequent performance analysis is obtained naturally as the design proceeds. A multitude of 'what-if' scenarios and sustainable alternatives can be assessed at the early stages of design and rapid changes made, when they are most beneficial in terms of more sustainable and cost effective designs. Recent technological advances in software development have been proven that SDA and BIM interoperability can and does work. Whilst it is not without its complications, it is constantly being improved and implemented [8].

3. Case Study - Energy Plus House, Hieron's Wood, UK

Hieron's Wood is a four bedroomed dwelling, currently being built in the garden of an existing 1920's house, situated in a former quarry (see Fig. 1a,b). The property is just within the Green Belt and on the edge of the sustainable settlement of Little Eaton, Derbyshire.
The design concept was to produce a building with a very low imprint on the site, related to the physical, historical and visual context within which it sits, adopting its character through the selection and use of materials.
Initial energy design calculations estimate that the house will produce more energy from the renewables than it will import externally. The innovative use of sycamore in a traditional form of construction is proposed, testing the low energy potential of highly insulated, breathable, traditional natural fabric that uses sustainable and locally sourced materials. The project represents a unique opportunity to undertake long term research in three key areas; monitoring of building performance with regard to energy consumption/embodied carbon/health and wellbeing; innovative use of materials and technology; and detail design and construction.

Fig. 1. (a) Aerial View - Site Location; (b) Site build progress - Feb 2015

The proposed house comprises (see Fig. 2. a,b):

- Lower ground floor containing an ensuite master bedroom, two ensuite guest bedrooms and a bed/study room; lower entrance hall, utility and a garden store accessed externally.
- Upper ground floor with an open living/dining/ kitchen area, larder, cloakroom/wc and entrance hall.
- A small mezzanine open study balcony incorporated within the upper living dining area
- A wide stair links the upper and lower ground floors and a light, glass stair accesses the mezzanine

Building exemplifies both proven and emerging green technologies alongside passive energy saving measures, such as a passive stack and earth tube ventilation (see Fig. 3b, 17 and 18). The design embodies the principles of 'fabric first' approach, through the creation of a highly insulated, breathable building, constructed using local materials and harnessing local resources and craft skills (see Fig. 3a). Both sycamore and dry stone walling is sourced within the compounds of the site, situated in the former quarry. The proposed house takes full advantage of the site's sloping southerly aspect and far reaching views across the valley, whilst harnessing the power of the sun to meet demand for electricity and hot water.

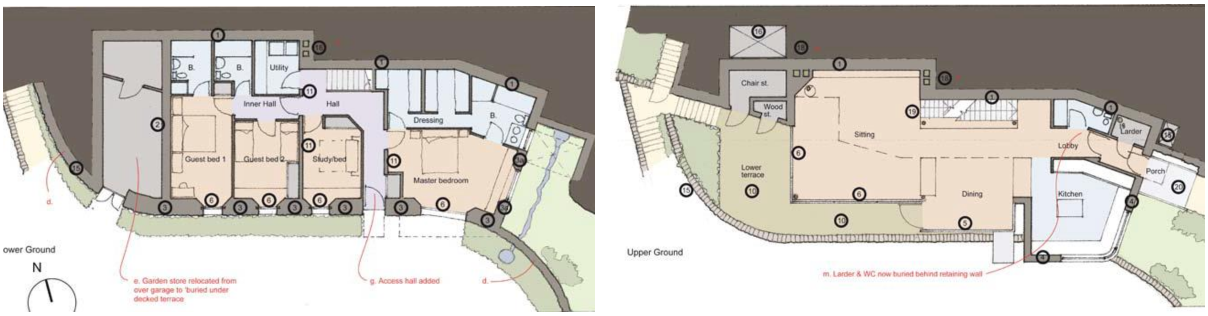


Fig. 2. (a) Lower ground floor ; (b) Upper ground floor

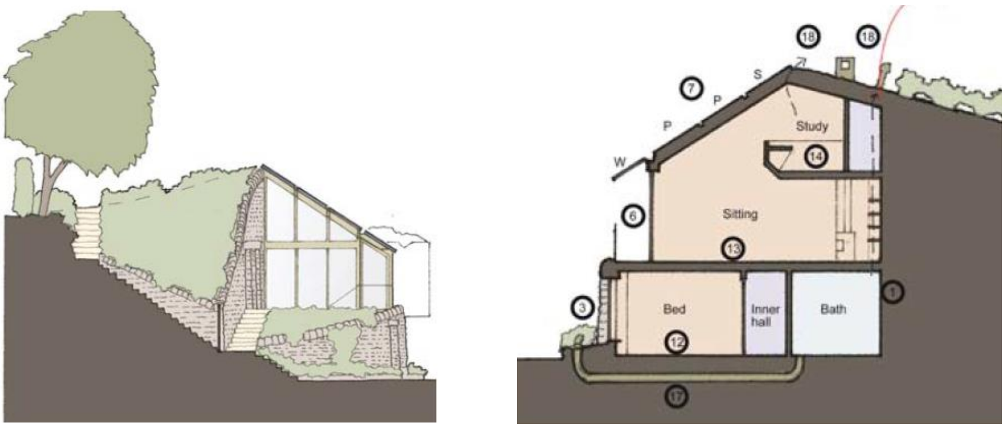


Fig. 3. (a) West Elevation ; (b) Section with numerical reference to rooms/design features

3.1. Approach to Sustainable Design and BIM Integration

There are three key areas of proposed research undertaken; including one novel aspect of construction:

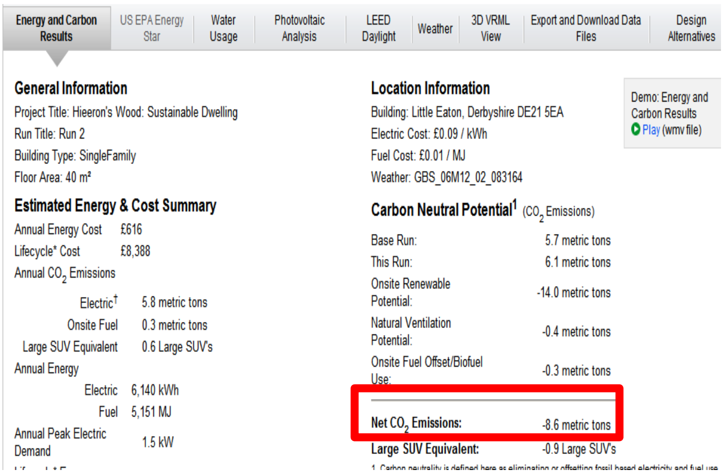
- Innovative use of sycamore (structural)
- Use of hemp/lime composite (constructional)
- Integration of BIM and SDA and evaluation of the building design and performance in terms of its environmental sustainability, through all stages of the project. Testing the use of breathable and low embodied carbon materials and traditional concepts. Use of the proposed development as a 'test bed' for long term performance monitoring, via integration between BIM and SBE (Smart Built Environment).

Fig. 4 encapsulates the project research philosophy of a true cycle of sustainable design, emphasising its iterative nature over the linear approach so often seen in current practice. The rationale behind the software choice was predominantly influenced by the ability of Autodesk © Revit, Green Building Studio and Ecotect to provide ease of iterations between conceptualisation and calculation stage.

Fig. 4. True Cycle of Sustainable Design

Source: Author, Autodesk © Revit, Ecotect and Green Building Studio, IES © <VE>, Dassault Systèmes © Solidworks

At the feasibility stage of design an early building massing model was created, based on concept drawings and sketch schemes. The site sustainability potential was investigated to define an optimal location, shape and building orientation, based on the concept and site environmental aspects. To get first round of feedback initial thermal analysis and energy use calculations were generated, based on a choice of not actual, but limited choice of predetermined building construction specifications (see Fig.5). Thus, a number of viable alternatives were rapidly created and their performance evaluated, without commitment to a "fixed" building construction and services specification so early in the design process.



ADL1: Para 1.16	Target U-Value		
Description	Value	Description	Value
Roof Area (Ar):	108.58 m²	Total Exposed Area (At):	544.89 m²
Ground Floor Area (Ag):	105.47 m²	Total Floor Area (Af):	367.33 m²
South Windows (Ws):	41.56 m²	North Windows (Wn):	0.00 m²
Target U-Value:	0.35 - (0.19*(Ar/At)) - (0.10*(Ag/At)) + (0.413*(Af/At))		0.571
SEDBUK Modifier:	(System / Reference) = (85.0 / 78.0)		1.090
Solar Gain Modifier:	0.04 × ((Ws - Wn) / Wt) = 0.04 × ((41.6 - 0.0) / 59.2)		0.028
BUILDING U-VALUE:	0.244	TARGET U-VALUE:	0.651
		RESULT:	PASSED

	Full Material Schedule			
Material	Surface Area (m²)	U-Value (W/m²K)	Shading Coefficient	Framing Ratio
Intermediate_Floor	260.98	0.15		
SolidCore_OakTimber	2.10	1.80		
North_Concrete_RW	140.04	0.09		
DoubleGlazed_Neo_Skylight	11.06	1.50	0.81	--
South_Stone_Cavity_Wall	94.50	0.17		
Internal_Partitions	192.00	1.20		
TripleGlazed_TimberFrame	30.01	0.80	0.81	--
DoubleGlazed_FineLine_TimberFrame	11.42	1.30	0.75	--
DoubleGlazed_Folding_Doorsets_1_5	6.74	1.50	0.75	--
Ground_Floor_Slab	105.47	0.15		
Timber_Frame_Wall	24.80	0.17		
Roof_Construction	108.58	0.12		

Fig. 5. (a) Carbon Neutral Potential Analysis ; (b) Initial Thermal Analysis

The design progressed to consider building energy consumption and costs, including water usage analysis and carbon neutrality potential (see Fig.5). As the design advanced the building's thermal zones were established (walls layout, fenestration, roofs, floors and internal partitions). The subsequent model was employed for final building shadow and sun studies, generating sun path and solar stress diagrams, room level calculations such as average daylight and artificial light factors, including visibility studies and solar exposure analysis [9], [10] (see Fig. 6).

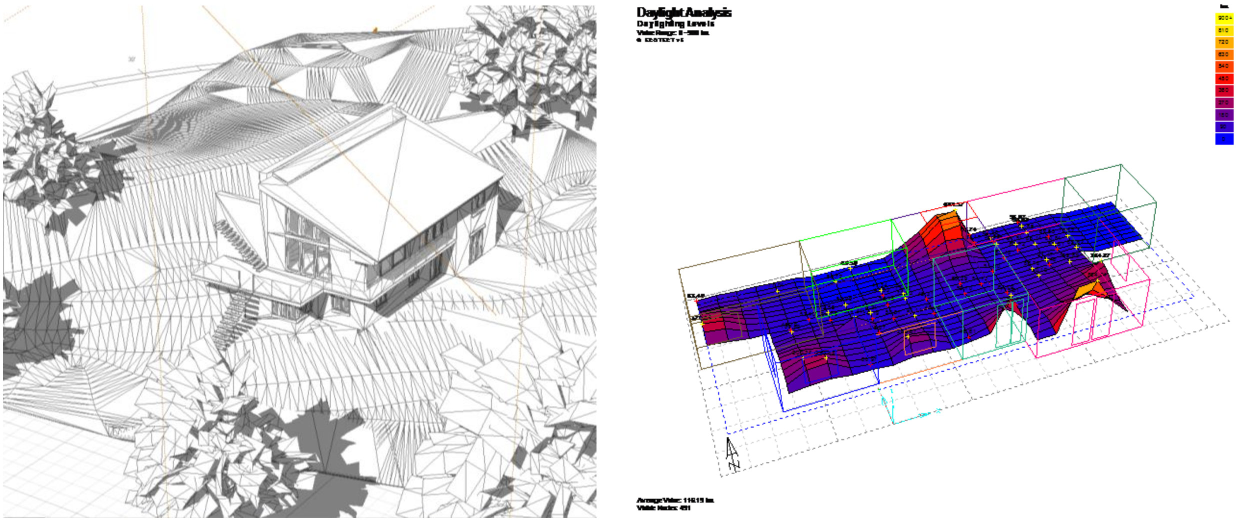


Fig. 6. (a) Solar Analysis Example, Summer Solstice 21st June, 16:00pm ; (b) Standard Overcast Daylight Analysis Example

At the final stage zone thermal templates, services and occupancy patterns were defined and software used to produce thermal performance calculations, including heating and cooling loads; passive gains and losses and incident solar radiation. Based on those results zones were rearranged and size and shape of apertures defined, including protection against excessive solar gains in the summer and choice of specific materials and U-values (see Fig.7). It was at this stage, after analysing different scenarios, that the design was 'fixed' and site work commenced. Due to the unique nature of the project and special arrangements with Building Control, detailed drawings are still being produced although the works on the site have already commenced (June 2014 start, June 2016 completion). Hence, once the BIM model is finalised and a full drawings package and performance specification produced, the model will be exported to IES for final energy analysis and building regulations compliance calculations [11]. Post completion, future research will concentrate on the long term monitoring and 'performance gaps', adding to the research by Innovate UK [12], via integration between BIM and SBE (Smart Built Environment) technologies [4].

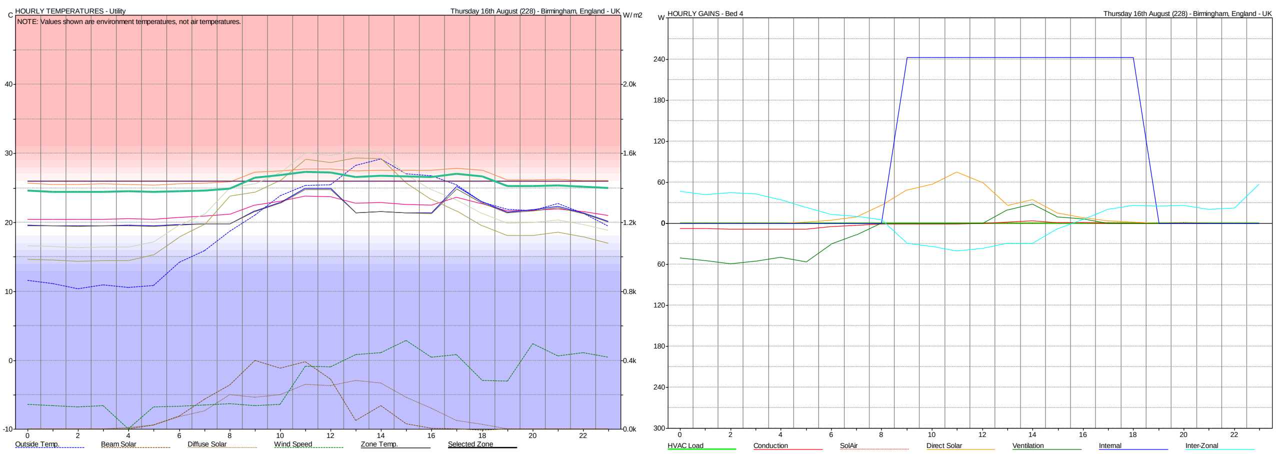


Fig. 7. (a) Example of Hourly Temperature Profile – Hottest Day (Average) Aug 16th ; (b) Hourly Heat Gains/Losses– Bed 4

3.2. Novel Structural Use of Sycamore for Construction in Britain

Acer Pseudoplanatus, generally known in the UK as sycamore, is a common but not native hardwood tree in British woodland, germinating and growing in almost all conditions. Mostly self-seeded or suckered it grows prolifically, often unwanted, almost like a weed. Once grown it creates a dark shade which deters most other tree species from germinating. Hence it beats most of the tree 'competition', which is the reason why it has been so successfully invasive and detrimental to the biodiversity of the woodland. Furthermore, sycamore has a low ecological count, that is to say it's leaves and bark support a very small variety of insect life, thereby attracting few birds and little other wildlife. As reported by [13], sycamore eco count is less than 25, compared to for example oak that has over 400. Its regular harvesting could create room for other species to grow and flourish and improve the ecological diversity of British woodland.

Sycamore is not used for structural purposes due to its perishability and susceptibility to rot and insect attack compared with other hardwoods [14]. However, its structural and constructional performance is understood to be no worse than most modern softwoods and comparative hardwoods, as reported in literature and confirmed in consultation with the Timber Research and Development Association (TRADA), [15]. Finding the right methods of structural/constructional use and the treatment for sycamore could potentially enable sycamore to be utilised on other projects as a new sustainable resource to supplement existing timber supplies, most of which are nowadays imported. It is however important to note that the sycamore is, by the nature of the project, sourced within the woodland of the site and thus the research results cannot be statistically extrapolated to a wider geographical area. Furthermore, as sycamore is a natural material, results of property value tests often differ significantly between individual specimens and due to the relatively small sample size cannot be considered to be statistically valid for other applications. The above however is to be expected and it does not undermine the importance of the Hierons Wood project as a precedent.

Desktop research has indicated that sycamore could indeed be used for structural and constructional applications, as long as due care is taken in its detailing for resistance to decay and insect attack, moisture control, ventilation provision and service class uses. Fig. 8 shows different service classes and required moisture contents, as follows:

Service Class	Examples of use in building	Typical upper moisture content in service
1	Warm roofs Intermediate floors Timber-frame walls, internal and party walls	12%
2	Cold roofs Ground floors Timber-frame walls, external walls External uses protected from direct wetting	20%
3	External uses, fully exposed	>20%

Fig. 8. Service Classes and Moisture Content, [16]

It is important to note that sycamore in Hierons Wood project will only be structurally used in the service classes 1 and 2, where it will be maintained at less than 20% moisture content and thus unlikely to be attacked by wood decaying fungi or sapstain [16]. This, coupled with the first line of defence through well resolved construction detailing and quality workmanship on the site, including use of preservatives as a second line of defence, should 'protect' sycamore against its worst enemy, perishability.

Although the hardwoods are visually graded in practice[17], for the benefit of research it was agreed with TRADA to test its mechanical structural properties as per BS EN 408:2010; namely local modulus of elasticity, bending and compression strength, as well as recording the density and moisture content of sample specimens. Whilst not certified for a commercial machine grading, the beam testing facilities at the University did allow for this analysis to take place, with the results shown below (for compression test results see Fig 9 and Table 1 and for bending Fig 10 and Table 2).

Table 1. Compression Test Results

Sample 50x50x300 (mm)	Density (kg/m^3)	Moisture Content (%)	Compression strength II to grain (N/mm^2)
1	566.8	14%	33.1
2	572.3	14%	37.3
3	582.8	14%	38.6
4	585.9	14%	41.3
5	591.2	14%	42.1
Avg	**579.80**	**14%**	**38.5**
SD	10.0	0.00	3.6

Fig. 9. Compression strength test (Source: Author)

Table 2. Bending Strength Test Results

Sample 50x50x1000 (mm)	Density (kg/m^3)	Moisture Content (%)	Local Modulus of Elasticity (N/mm^2)	Bending Strength II to grain (N/mm^2)
1	566.8	14%	9785	123.7
2	582.8	14%	9677	96.9
3	571.2	14%	9406	96.7
4	575.6	14%	9529	108.6
5	583.9	14%	9590	91.5
6	575.2	14%	9350	92.6
7	578.3	14%	9370	93.7
Avg	**576.3**	**14%**	**9530**	**100.5**
SD	6.1	0	165.1	11.7

Fig. 10. Bending strength test (Source: Author)

The results above are the first phase of mechanical properties testing, undertaken on 7 sycamore samples for bending and 5 for compression strength tests. The next phase, to be conducted in June 2015, will include at least another 5 samples for compression and 3 for bending, as per BS EN 408:2010 requirements, including the compression and bending strength testing of at least 10 samples of laminated sycamore (for each test).

Not withstanding the locality of sourcing and size of the sample, the initial results are comparable to published data, e.g. TRADA reports sycamore bending strength 99 N/mm^2, modulus of elasticity 9400 N/mm^2, density 630 kg/m^3 and compression parallel to grain 48 N/mm^2, [15]. The results are fully included in the project BIM LOD:400 (Level of Development) via new material specification [19].

3.3 Earth Tube Analysis

The aim of this part of the research was to undertake a study into the effectiveness of an earth tubes system as part of the passive ventilation and cooling strategy for the energy plus house at Hieron's Wood, with the following variables considered; zone volume, required air change rate; pipe layout (grid, ring, serpentine), pipe depth, soil and climatic conditions and ground water level. A single polypropylene pipe with an inner silver antimicrobial layer was chosen, with nominal diameter of 315 mm and outlets to bedrooms of 200 mm diameter [18]. Total pipe length is 54.3 meters, excluding inlets and outlets. The design and parameters selection was finalised in collaboration with ARUP. The tube air inlet is on the North-West side of the site, at 85.600 meters AOD. It then penetrates the ground and drops 3.74 meters before reaching the level of foundations in front of the house, as shown in Fig. 11b. The lowest point is -302.5 mm below the edge beam. The study confirmed that the earth tube parameters were coherent with the geometry of the building, the topography of the site and its orientation. Analytical calculations and computational fluid dynamics (CFD) simulation using Dassault Systèmes © Solidworks [Fig. 11b], exported from the federated BIM model, confirmed that the design choices made (length, orientation, diameter, pipe material, etc.) are suitable, with a system discreet efficiency of almost 70% [18].

Fig. 11. (a) Earth Tube CFD Analysis ; (b) Earth tube during construction

4. Discussion and Conclusions

This case study based research presents the method and technology for integration of sustainable design analysis (SDA) with building information modelling (BIM). The feasibility stage of SDA comprised an early building massing modelling, after which the site sustainability potential investigation was conducted through use of environmental software. Initial thermal analysis and energy use calculations in Autodesk Green Building Studio were generated using a predetermined number of building construction specifications, thus allowing for building energy calculations to be generated without the commitment to exact specification of buildings components. The approach required a lower level of development (LOD) with LOD:100 to LOD:300 employed [19], resulting in generally less computational/modelling effort needed. In addition, the final stage of Building Regulations Part L compliance calculations was reached with a lot greater level of certainty in terms of its requirements.

The SDA and BIM integration led to the following BIM federation model and attribute data issues. Firstly, a better solution for zone surface and volume recognition problems is required with an improvement to poor bi-directional links between models needed, as often leads to ‘modelling-twice’. Furthermore, the performance degradation was an issue with too many parameters attempting to be interoperable, thus affecting performance. Interpretation of BIM elements is overcomplicated by SDA software, leading to the loss of parametric intelligence. Finally, in terms of software employed in this research, it was somewhat US orientated, in particular in relation to the codes for sustainable assessment.

Wider research concludes that the despite the sustainable drivers, interest in SDA exceeds its practical application and hence its integration within small to medium practices is not likely to be achieved in the near future. Whilst it could be argued that sustainable design only happens if it can be afforded, it remains the case that the benefits of correct decisions at the early stages of design can significantly exceed the investment required in the first place. This is best understood via ”MacLeamy Curve” [20]. At early stages of the project the cost of design changes is at its lowest, but the ability to impact the overall project costs is at its highest. This ability diminishes as the design progresses whilst the cost of changes increase. Thus, the ability to control costs and the effort required to make changes is at its most beneficial at early stages of design.

5. Future Research

Further research will concentrate on the integration of BIM, SDA and SBE (Smart Built Environment) technologies for long term performance monitoring, using the proposed development as a 'test bed'. Sycamore performance monitoring will include moisture content together with temperature and relative humidity of its immediate surroundings. In addition, digital micro probe (DmP) will be used as a reliable and non-destructive method for detection and analysis of wood decay [21]. Performance monitoring of the earth tube system will include humidity, temperature, CO_2 and VOCs in terms of air quality, but also air speed and the pressure [22], [23]. Furthermore, additional CFD simulations will be conducted to compare real results with those produced by the desktop software simulation. Hempcrete performance monitoring will include temperature and relative humidity, but also heat flux sensors to monitor dynamic changes of U-value as it goes through its intermittent periods of wetting and drying.

6. Acknowledgements

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